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The first 8–13 μm spectra of globular cluster red giants: circumstellar silicate dust grains in 47 Tucanae (NGC 104)

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Abstract. We present 8–13 μm spectra of eight red giants in the globular cluster 47 Tucanae (NGC 104), obtained at the European Southern Observatory 3.6m telescope. These are the first mid-infrared spectra of metal-poor, low-mass stars. The spectrum of at least one of these, namely the extremely red, large-amplitude variable V1, shows direct evidence of circumstellar grains made of amorphous silicate.

Key words. Stars: AGB and post-AGB – circumstellar matter – Stars: evolution – Stars: mass-loss – globular clusters: individual: 47 Tucanae (NGC 104) – Infrared: stars

1. Introduction

Galactic globular clusters offer us an opportunity to study the late stages of evolution of stars with a main sequence mass ~ 0.8 M$_\odot$ at an accurately known distance. These clusters span a range in metallicity from [Fe/H]< -2 to ~ 0, allowing studies of the dependence on metallicity over more than two orders of magnitude. As the most populous star clusters in the Galaxy, they also harbour rare examples of short-lived phases in stellar evolution.

Of particular interest for the evolution of low-mass stars and their rôle in galactic evolution is the loss of ~ 30 per cent of their mass during post-Main Sequence evolution. Some of this occurs prior to the core helium burning stage, near the tip of the first ascent Red Giant Branch (RGB), and some on the Asymptotic Giant Branch (AGB). Alfvén waves generated in chromospherically active giants may drive mass loss at rates of $\dot{M} \sim 10^{-7}$ M$_\odot$ yr^{-1} (Pijpers & Habing 1989; Judge & Stencel 1991; Schröder & Cuntz 2005), but in the coolest giants a combination of strong radial pulsations with circumstellar dust formation may facilitate a radiation-driven wind with $\dot{M} \sim 10^{-6}$ M$_\odot$ yr^{-1} or more (Gehrz & Woolf 1971; Bowen & Willson 1991; Winters et al. 2000). Very little is known about the dependence of dust-driven winds on metallicity (van Loon 2006).

Infrared (IR) emission from circumstellar dust has been detected in several globular clusters (Ramdani & Jorissen 2001; Origlia et al. 2002), most notably in 47 Tucanae — a massive cluster at 5 kpc (Gratton et al. 2003), with [Fe/H]$=-0.66$ (Carretta & Gratton 1997). We here present the first mid-IR spectra of globular cluster red giants, obtained to identify the nature of the dust grains.

2. Observations

2.1. Spectroscopy

The Thermal Infrared MultiMode Instrument (TIMMI2) on the 3.6m telescope of the European Southern Observatory (ESO) at La Silla, Chile, was used on the two nights of 19–21 October, 2005, to obtain low-resolution ($\lambda/\Delta\lambda \sim 160$) 8–13 μm spectra of a sample of luminous red giants in 47 Tuc. We used a slit with a width of 1.2$''$ on all occasions except for V18+V11 which were observed simultaneously in a 3$''$ slit. The IR technique of chopping and nodding was used, with a throw of 8–15$''$ depending on possible confusion. Total integration times were 1 hour per target star spectrum (10 min for V2).

The target star spectra were divided through by the spectrum of a K-type standard star taken close in time ($\sim$ 1 hour) and airmass (about ± 0.1) to the observation of the target star. This removed most of the telluric features, of which the ozone band around 9.5 μm is the most conspicuous. To correct for the photospheric spectrum of the standard star, the thus obtained quotient spectra were multiplied by template spectra representative for the standard stars used (Cohen et al. 1999).

The data were reduced using the TIMMI2 pipeline and long-slit spectroscopic procedures in the ESO Munich

Image Data Analysis System (ESO-MIDAS). The spectra were extracted by applying weights to the rows on the array parallel to the dispersion direction, based on the signal in the row after subtraction of a polynomial fit to the remaining sky background in the cross-dispersion direction.

2.2. Photometry

We calibrated the acquisition images of the target stars against those of the standard stars (van der Bliek, Manfroid & Bouchet 1996; Cohen et al. 1999). These were taken through the N1 filter (8.6 μm; width from 8.0 to 9.2 μm at half maximum). Aperture photometry was obtained in ESO-MIDAS using an aperture diameter of 2.4″. A zero point of 57.8 Jy was adopted (van der Bliek et al. 1996). The resulting photometry is listed in Table 1, where the uncertainty includes an 11 per cent calibration uncertainty added in quadrature to the measurement error.

Conditions were good. The humidity ranged between 30–50 per cent and the air temperature between 10–12 °C. With an optical seeing of 0.3–1.1″ the mid-IR observations were always diffraction limited (0.6″ at 10 μm).

2.3. Targets

We selected all stars in 47 Tuc for which the possibility of IR excess emission has been suggested on the basis of ISO imaging (Ramdani & Jorissen 2001; Origlia et al. 2002), plus the two most extreme AGB stars in 47 Tuc, V1 and V2 (Frogel & Elias 1988). The V numbers are according to Sawyer-Hogg (1973), and the LW numbers are new variables found by Lebzelter & Wood (2005). From this sample of 11 targets we took spectra of the brightest 7 sources, together with V11 not on our target list but which could be placed in the slit simultaneously with the observation of the target V18. The acquisition images of the target LW19 revealed the likelihood of source confusion in the ISO data, and no spectrum was taken.

We list in Table 1 the photometric periods, P, and 2.2 μm magnitudes, [2.2], from Lebzelter & Wood (2005). The [2.2] values are averages of the observed maxima and minima based on photometry obtained from the literature, and are thus representative of the mean brightness. It was based in part on the work by Frogel, Persson & Cohen (1981), who collected JHK and intermediate-band CO and H_2O photometry for red giants in 47 Tuc, including V 1–3 that were found to be too bright to be RGB stars and therefore must be on the AGB. These stars were also found to exhibit the strong molecular absorption bands that are characteristic of cool, pulsating AGB stars.

Table 1. List of targets, in order of increasing Right Ascension (J2000), their photometric periods and 2.2 μm magnitudes from Lebzelter & Wood (2005), and our 8.6 μm magnitudes. Uncertain values for the pulsation period are trailed by a colon.

Name	α ($^{\rm h\ m\ s}$)	δ ($^\circ\ '\ ''$)	P (d)	[2.2]	[8.6]
LW10	00 24 02.6	−72 05 07	121:	6.40	6.37 ± 0.25
V26	00 24 07.9	−72 04 32	65:	6.25†	6.11 ± 0.22
V8	00 24 08.3	−72 03 54	155	6.70	5.56 ± 0.21
V1	00 24 12.4	−72 06 39	221	6.21	5.19 ± 0.26
V2	00 24 18.4	−72 07 59	203	6.29	5.45 ± 0.16
V18	00 25 09.2	−72 02 39	83:	7.47	7.01 ± 0.48
V11	00 25 09.0	−72 02 17	160:	6.71	6.67 ± 0.29
V3	00 25 15.9	−72 03 54	192	6.27	5.72 ± 0.18

† Blend in 2MASS; Origlia et al. (2002) list $K = 6.55$ for V26.

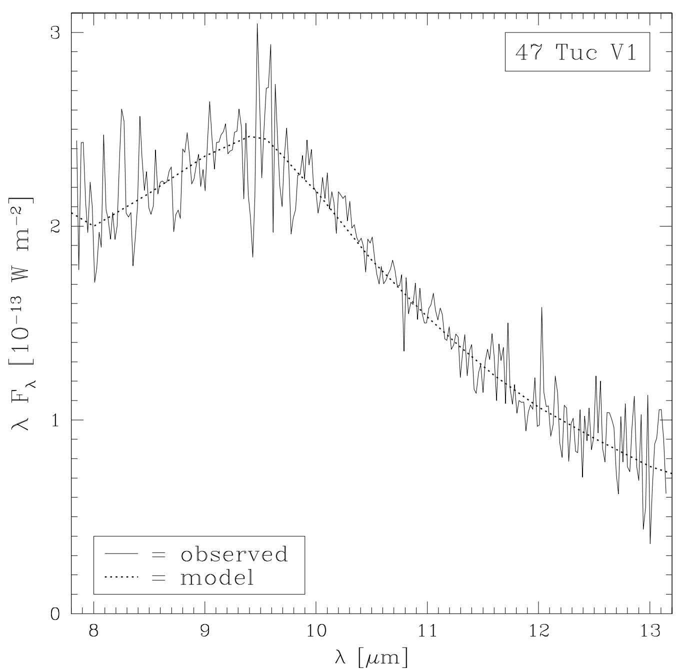

Fig. 1. Observed 8–13 μm spectrum of 47 Tuc V1 (solid) and a DUSTY model spectrum (dots). The broad emission around 9.5 μm is due to amorphous silicate grains.

3. Description of the spectra

3.1. Silicate grains in the Mira-type variable 47 Tuc V1

The reddest and most luminous variable star in 47 Tuc, V1 shows clear evidence for dust in its 8–13 μm spectrum (Fig. 1) in the form of broad emission peaking around 9.5 μm, on top of a continuum that is significantly less steep than that of a stellar photosphere. None of the sharp features in the spectrum are real.

An excellent fit to the observed spectrum is obtained with the radiative transfer model DUSTY (Ivezić, Nenkova & Elitzur 1999), using amorphous silicate grain properties from Draine & Lee (1984). We assume a grain bulk density of 3 g cm^{-3} and a standard MRN grain size distribution (Mathis, Rumpl & Nordsieck 1977), and a stellar effective temperature of 3400 K (Lebzelter & Wood 2005). The best fit was obtained for a dust temperature at the inner edge of the envelope of 700 K. The radial density profile was computed by DUSTY using a radiation-driven dust wind formalism (Ivezić & Elitzur 1995).

The best fit required a luminosity of 7300 $L_\odot$, and an optical depth of 0.15 at a wavelength of 0.55 μm. Assuming that the gas-to-dust ratio, ψ, scales linearly with metallicity and that $\psi_\odot = 200$ (van Loon, Marshall & Zijlstra 2005), we thus estimate a total (gas+dust) mass-loss rate $\dot{M} = 1.0 \times 10^{-6}$ $M_\odot$ yr^{-1}. The terminal wind speed is predicted by DUSTY to be 5 km s^{-1}.

3.2. Mid-IR spectra of other red giants in 47 Tuc

The spectra of the other targets (Fig. 2) are displayed together with the template spectrum for the nearby Main Sequence star γ Crux of spectral type M3.5 (a temperature similar to that of the target stars), after scaling it to match the 2.2 μm brightness of the target stars. With $[2.2]_{\rm 2MASS} - [8.6] = -0.02$ mag, γ Crux shows no evidence for dust emission. The spectra of the faint targets 47 Tuc V11, LW10 and V26 follow exactly the scaled template spectrum, and hence their spectral energy distributions can be considered purely photospheric in origin. The faintest star in our sample at 2.2 and 8.6 μm, 47 Tuc V18 shows a broad emission "feature" above the photospheric continuum, without a clear peak. The brightest objects, 47 Tuc V3, V8 and V2 are clearly much brighter at mid-IR wavelengths than the photospheric template, but curiously they do not show a discrete emission feature that could have helped identify the type of dust.

4. Discussion

4.1. Red giants in 47 Tuc which exhibit IR excess

The stars with the reddest [2.2]–[8.6] colours tend to have the longest pulsation periods and highest luminosities, and straddle the sequence that in the Large Magellanic Cloud (LMC) has been identified with stars pulsating in the fundamental mode (Fig. 3a; Wood et al. 1999; Ita et al. 2004). The four reddest stars are all Mira-type variables characterised by regular pulsations with a large amplitude in luminosity and velocity (Lebzelter et al. 2005; see also Frogel & Whitelock (1998) and Feast, Whitelock & Menzies 2002). The only object without a red [2.2]–[8.6] colour that nevertheless appears to pulsate in the fundamental mode is 47 Tuc V11, whose pulsation period is uncertain and probably shorter than the 160 days we list here (Lebzelter & Wood 2005).

The [2.2]–[8.6] colour correlates better with the 8.6 μm magnitude (Fig. 3c) than with the 2.2 μm magnitude (Fig. 3b). Variability could have affected the [2.2]–[8.6] colour at the level of a few 0.1 mag; the [2.2] magnitudes are mean values but the [8.6] magnitudes are single-epoch measurements. The amplitude at 8.6 μm is generally less than at 2.2 μm, where stars 47 Tuc V 1–3 are known to vary by about half a magnitude (Frogel & Elias 1988; Le Bertre 1993). The absence of negative values for [2.2]–[8.6] in our data suggests that the red colours for 47 Tuc V 1–3 and V 8 can not simply be explained by variability. It is not *a priori* clear whether the red colours are due to excess emission from circumstellar dust grains or simply the result of a very cool photosphere. For comparison, the TIMMI2 standard stars (mostly K-type giants) have $[2.2]_{\rm 2MASS} - [8.6] = -0.2$ to $+0.1$ mag.

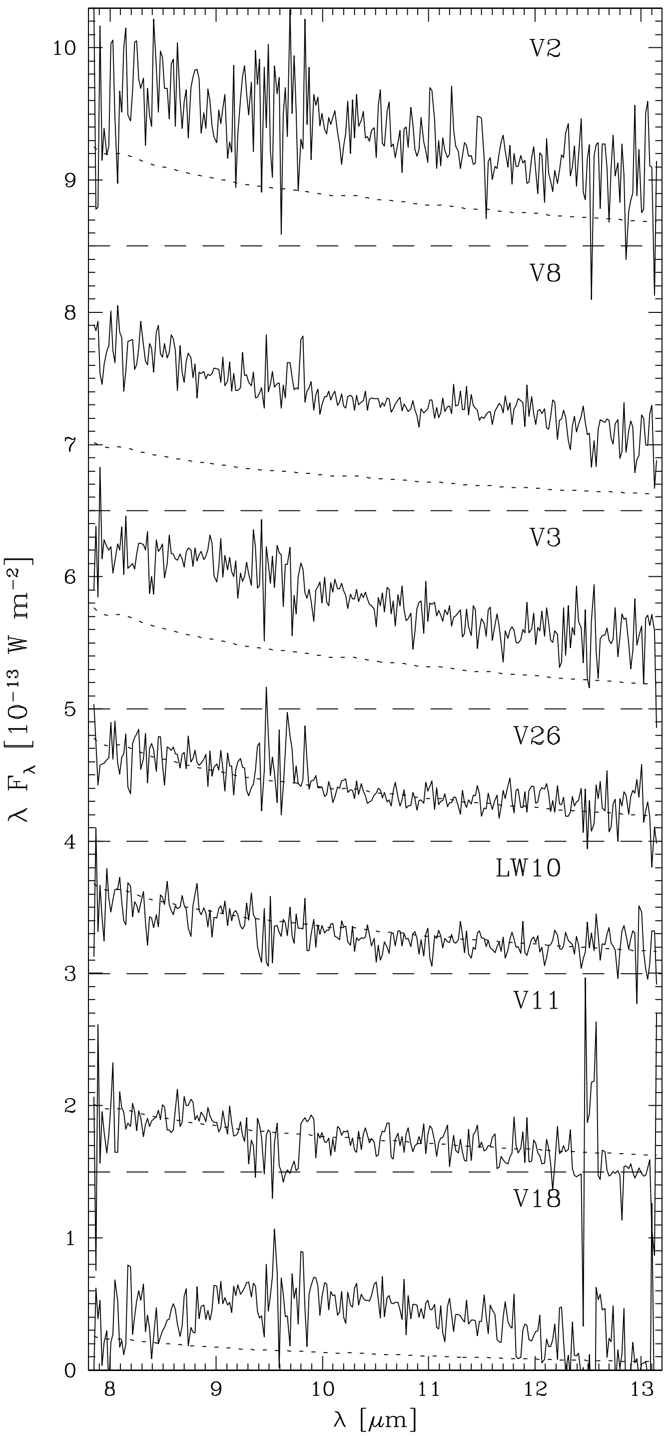

Fig. 2. The 8–13 μm spectra for the other targets in 47 Tuc, in order (from bottom to top) of increasing 8.6 μm brightness. The dashed line indicates the zero-level for each spectrum. The dotted curve is the template spectrum for M3.5 V star γ Crux scaled to match the 2.2 μm flux density of the target star.

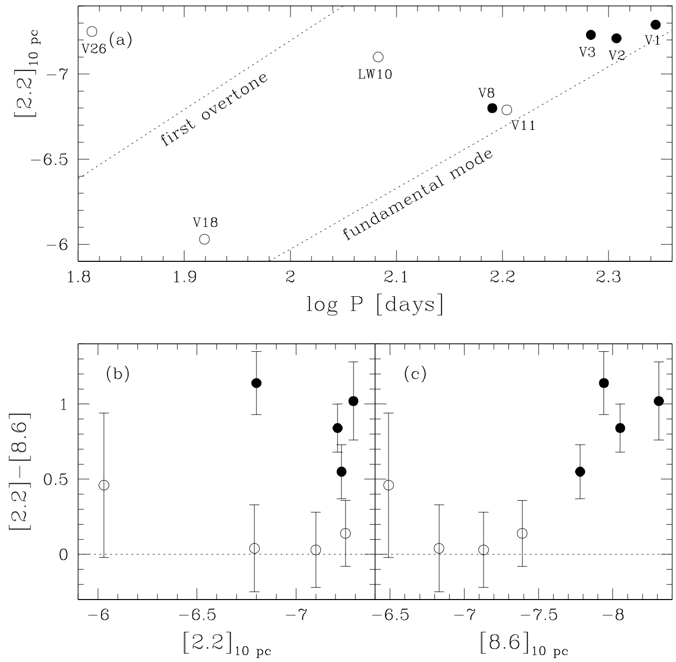

Fig. 3. Absolute magnitude at 2.2 μm versus pulsation period (a), and [2.2]–[8.6] colour versus absolute magnitude at 2.2 μm (b) and 8.6 μm (c). Objects with [2.2]–[8.6]> 0.5 mag have solid symbols. The two sequences in the $[2.2]_{10\mathrm{pc}}$ versus P diagram are from stars in the Large Magellanic Cloud (Ita et al. 2004).

47 Tuc V18 has a reddish [2.2]–[8.6] colour still consistent with purely photospheric emission. Ramdani & Jorissen (2001) measured a 12 μm excess of more than a magnitude, making it the reddest object in their sample. Apparently, the dust emission only becomes obvious longward of 9 μm (Fig. 2). Lebzelter et al. (2005) propose that this star has recently experienced a thermal pulse.

The measurement by Ramdani & Jorissen (2001) of the nearby 47 Tuc V11 is in perfect agreement with our measurement, showing no evidence of excess emission. The mild excess for 47 Tuc V3 in their data is also consistent with our measurement. Of the three objects in common with Origlia et al. (2002) we only detect possible excess emission in 47 Tuc V8, whilst the [2.2]–[8.6] colours of 47 Tuc LW10 and V26 are consistent with purely photospheric emission despite large K–[12] colours measured by Origlia et al. (2002). It is possible that some of these ISO data suffer from confusion.

4.2. Dusty winds of metal-poor, low-mass AGB stars

Of all members of 47 Tuc, V1 has the longest pulsation period, largest pulsation amplitude, coolest photosphere, and highest luminosity. It does not therefore come as a surprise that it is this star that shows the most convincing evidence for circumstellar dust.

Dijkstra et al. (2005) suggest a sequence for oxygen-rich grain mineralogy, whereby emission from amorphous alumina (Al_2O_3) grains at 11–13 μm (Speck et al. 2000) dominates the spectrum of stars with relatively low mass-loss rates and emission from amorphous silicate takes over at higher mass-loss rates. The reason given is that alumina has the highest condensation temperature of all known dust grain species, at $\sim$ 1500 K in a typical circumstellar environment. Silicates condense onto alumina seeds, obliterating the signatures of the alumina in dense winds (Tielens 1990). Although the alumina is seen at mass-loss rates of $\dot{M} \sim 10^{-6}$ M$_\odot$ yr^{-1} in massive AGB stars in the Large Magellanic Cloud (LMC), there is no trace of it in the spectrum of 47 Tuc-V1. One could speculate that the slower and more compact wind of this metal-poor, low-luminosity star reduces the volume of the wind that hosts bare alumina particles.

Compared to dust-enshrouded intermediate-mass AGB stars (van Loon et al. 1999) the mass-loss rate of 47 Tuc V1 is with $\dot{M} = 1.0 \times 10^{-6}$ M$_\odot$ yr^{-1} not very high, but sufficient to drive a wind by means of radiation pressure on the dust grains (Winters et al. 2000). There are a few hundred stars observed in 47 Tuc (Alves-Brito et al. 2005) that are in the last 10^8 years of their AGB evolution (Girardi et al. 2000, their models for $M = 0.8$ M$_\odot$ and $Z = 0.004$). This suggests that the phase in which we now find 47 Tuc V1 lasts a few 10^5 yr, during which a few 0.1 M$_\odot$ is lost. Like in intermediate-mass AGB stars (van Loon et al. 2005), much of the mass loss from metal-poor, low-mass AGB stars appears to be in the form of a dust-driven wind. Because this phase is so brief, only very few such objects (if any) are expected to be present in a globular cluster at any time. The amount of gas and dust to be lost by 47 Tuc V1 is very similar to that found in the interstellar medium of the massive globular cluster M 15 (Evans et al. 2003; van Loon et al. 2006).

5. Summary of conclusions

We presented the first mid-infrared spectra of red giants in a galactic globular cluster, 47 Tucanae. The most evolved object, 47 Tuc V1 is found to be surrounded by dust grains made of amorphous silicate, and to experience mass loss at a rate of $\dot{M} = 1.0 \times 10^{-6}$ M$_\odot$ yr^{-1}.

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